Effects of High Doses of Ionizing Radiation on Interface Properties of MOS Capacitors

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The generation of defects near the interface of Metal/Oxide/Semiconductor (MOS) capacitors has been studied after exposure to ionizing radiation with dosages of up to 500 Mrad (Si). Apparent dopant concentration reduction is observed, and its characteristics are analyzed as a function of device size, total dosage, initial damage level, and time evolution. The dependence of dopant reduction with ionizing radiation dosage indicate a behavior in the form $\Delta N/N_0 \sim (dose)^\alpha$, where $1/2 \leq \alpha \leq 1$ after a least square fitting to the power law. The range for possible values of α depends on processing parameters and device history prior to irradiation. The experimental results suggest a correlation between the dopant reduction and the density of interface traps generated during and after exposure to ionizing radiation.

I. Introduction

Due to its importance in silicon technology, the SiO_2/Si interface has been extensively studied in the past thirty years[1−4]. Nevertheless, the study and modeling of defect generation processes in MOS devices continues to unveil new and very interesting physical phenomena, most often associated to thin film growth or deposition and the damage caused in these regions by ionizing radiation (e.g. x-ray, plasma, e-beam, etc.)[5,6]. Therefore, from the scientific and technological aspects it is of great interest to understand the effects induced in the vicinity of the SiO_2/Si interface after exposure to high levels of ionizing radiation.

Among various interesting phenomena in irradiated devices, the apparent dopant reduction effect has been reported in the past after exposure of MOS structures to electron beam, x-ray and plasma irradiation or carrier injection through the SiO_2 layer. These authors have attempted to model the observed dopant reduction effect by proposing either dopant deactivation in silicon[3−5] or deep level traps[6] generated during the irradiation process. However, the origin for the dopant reduction effect has not been clearly established yet. In particular, the fact that the dopant reduction continues to increase in irradiated samples even after the radiation has ceased has not been reported as will be discussed in the next sessions.

In this work we present new effects associated to the dopant reduction phenomena, which show how defects are generated, and its behavior in the neighborhood of the SiO_2/Si interface when MOS capacitors are exposed to x-ray doses of up to 500 Mrad (Si). In particular the reduction of apparent dopant concentration near the interface is studied as a function of ionizing radiation dose, device size and post irradiation time interval. The results suggest that the dopant reduction behavior is correlated to the density of interface traps in the silicon band gap and its post irradiation dynamics unveil new phenomena not reported in previous works[3−6].

II. Experimental details

The MOS capacitors used in this work were fabricated using silicon wafers (100) oriented, p-type, two inch diameter, and of 1 Ω-cm resistivity. The wafers were cleaned following a standard RCA cleaning process[7], except for the last step, where the wafers were immersed either in a HF dip solution, 3% HF in deionized water (fluorinated samples), or in methanol (control samples) just prior to furnace loading. The first procedure is known to leave the silicon surface hydrophobic, therefore aiding in cleaning the surface and removing all possible native oxide. Further, the fluorinated samples have the intrinsic stress at the SiO_2/Si interface relaxed producing devices that are up to one order of magnitude improved in its radiation sensitivity[2]. The oxides used in the experiment range in thickness 500-2500 Å and were grown in dry O_2 in a Thermco MB-80 furnace at 1000 °C, followed by an in situ dry N_2 annealing at the growth temperature for 30 minutes. The thickness of the grown thermal SiO_2 was measured using an Auto El-IV Rudolph Ellipsometer at several wavelengths. For each wafer oxidized ten points were measured along its diameter to verify oxide uniformity, which was better than 3% in most cases. Aluminum films approximately 2000 Å thick were thermally evaporated from a W boat onto the oxide surface, and photolitographically defined to form circular gates with area in the range from 1×10^{-4} to 2×10^{-2} cm^2. After backside metallization, the wafers were annealed in forming gas at 400 °C for 30 minutes. The radiation source was an x-ray beam generated from a W target bombarded by 40 KeV, 20 mA electrons. The samples were characterized by the high frequency and quasi-static C-V measurements.

III. Results and discussion

Fig. 1 presents the high frequency (solid lines) and quasi-static (dashed lines) capacitance-voltage (C-V) curves measured at room temperature for a MOS capacitor fabricated in a p-type substrate (a) just before irradiation, and after total x-ray irradiation dosages of (b) 115 Mrad (Si) and (c) 500 Mrad (Si). From the quasi- static C-V curves one can notice, by comparison, the fast saturation of the density of interface traps in the Si band gap due to the high dosage of ionizing radiation (curves a and b). However, analyzing the high frequency curves two effects can be distinguished: (1) the negative voltage shift, reflects the generation of positive oxide charge near the SiO_2/Si interface due to electron-hole pair generation by the radiation, and (2) for the dosages presented, the values of the inversion capacitance are decreasing with increasing dosage of ionizing radiation. We have obtained other experimental data similar to these, for samples with different parameters, that have presented dopant reductions up to one order of magnitude from its initial value just prior to irradiation.

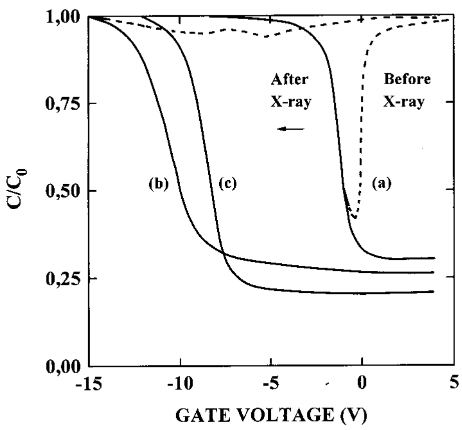

Figure 1. High frequency (solid lines) and quasi-static (dashed lines) C-V curves for a MOS capacitor measured (a) before irradiation, (b) after 115 Mrad (Si), and (c) after 500 Mrad (Si). Device size is 1.78×10^{-2}cm^2, and $d_{ox} = 600$Å.

This effect of apparent dopant reduction, was first reported by Sah et al.[3-5], and further studied by Wei and Ma[6]. In their paper Wei and Ma suggest the possibility of deep level generation by low-energy ionizing radiation. Majority carriers being trapped in these levels, associated to strained bonds, would produce the observed dopant reduction effect. Prior to this study we have performed DLTS (Deep Level Transient Spectroscopy), and Spreading Resistance measurements and found no evidence of deep level generation by x-ray irradiation with dosages of up to 500 Mrad (Si). Instead, our results strongly suggests a correlation between dopant reduction and interface trap density near the SiO_2/Si interface, as will be discussed next.

Fig. 2 shows the interface trap density (D_{it}) for (a) control and (b) fluorinated MOS capacitors after x-ray irradiation of 0.3 and 2 Mrad (Si) respectively, as a function of the gate area. As one can clearly see, for the fluorinated samples, there is almost no size dependence in comparison to the control samples. This has been explained in terms of intrinsic stress relaxation on the fluorinated samples[2], the ones which has been used throughout this work. In order to compare this behavior to the dopant reduction effect near the SiO_2/Si interface we have irradiated to several dosages, capacitors with different gate areas. Fig. 3 shows this dependence, and we observe the similarity to the Dit data in Fig. 2. The weak dependence for low and high doses is possibly due to stress relaxation near the interface as has been shown for interface traps, to be originated due to impurity incorporation near the interface during device processing[2]. In both cases the behavior is almost constant with gate dimension and in the case of dopant reduction there is a tendency for a small decrease of $\Delta N/N_0$ for devices with areas smaller than $1\times10^{-2}\text{cm}^2$. The results shown in figures 2 and 3 clearly indicate a similarity in behavior for both dopant reduction and interface trap density as a function of device gate area.

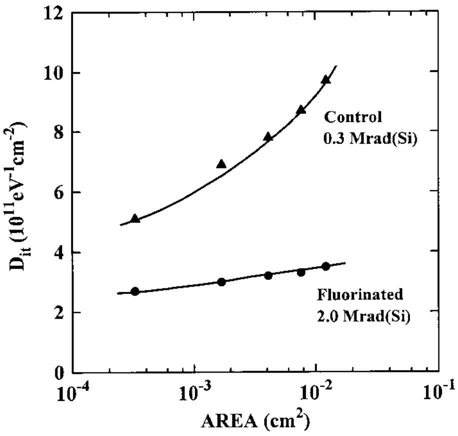

Figure 2. Interface Trap Density (D_{it}) as a function of device gate area for (a) control sample, 0.3 Mrad (Si), and (b) fluorinated sample, 2 Mrad (Si). $d_{ox} = 550$Å.

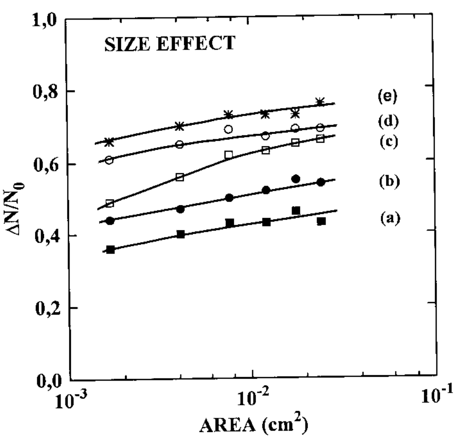

Figure 3. Apparent Dopant Reduction in MOS capacitors as a function of device gate area with total dosages of x-ray irradiation as a parameter. $d_{ox} = 2200$Å. After (a) 115 Mrad, (b) 180 Mrad, (c) 265 Mrad, (d) 417 Mrad, and (e) 500 Mrad (Si).

In figure 4 the dopant reduction effect for dosages up to 500 Mrad (Si) is shown for several devices having the gate area as a parameter, and again it is clear that no pronunciated size dependence is found for devices with gate areas in the range from 1×10^{-4} to $2\times10^{-2}\text{cm}^2$. Two important aspects of the dopant reduction effect are evident, and were found along the course of many experiments using a large variety of samples. First, as illustrated in the figure, we have found that there exists a threshold dosage ($(dose)_{th} \sim 20Mrad(Si)$) above which the dopant reduction effect is observed. Below this threshold dose no significant changes in the inversion capacitance is observed. Second, the behavior of the dopant reduction effect with dosage is found to follow a universal power law in the form $\Delta N/N_0 \sim (dose)^\alpha$, where $1/2 \le \alpha \le 1$.

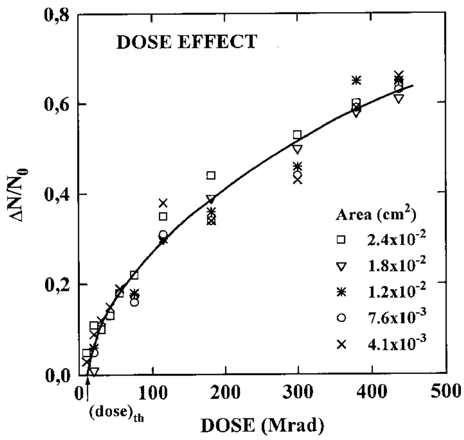

Figure 4. Apparent Dopant Reduction in MOS capacitors as a function of total dosages of x-ray irradiation for devices with varying gate area. $d_{ox} = 600$Å. Notice the threshold dosage $(dose)_{th} \sim 20$Mrad(Si).

To further understand these effects, we have irradiated samples that went through the same processing and had similar oxide and stress parameters. Fig. 5(a) shows the behavior of the dopant reduction effect as a function of total x-ray dose (0 to 500 Mrad (Si), and figure 5(b) the interface trap density behavior as a function of x-ray dose in the range of 0 to 20 Mrad (Si)). The smaller maximum irradiation dosage in the later was necessary in order to prevent saturation of the quasi-static C-V curves which provide the interface trap density. In both cases the results indicate a functional behavior in the form $\Delta N/N_0 \sim (dose)^\alpha$, where $\alpha = 0.57$, and $\Delta D_{it}/D_{it0} \sim (dose)^\beta$, with $\beta = 0.60$ after a least square fitting to the power law. These results suggest that the dopant reduction effect follows the behavior of the interface trap increase near the SiO_2/Si interface.

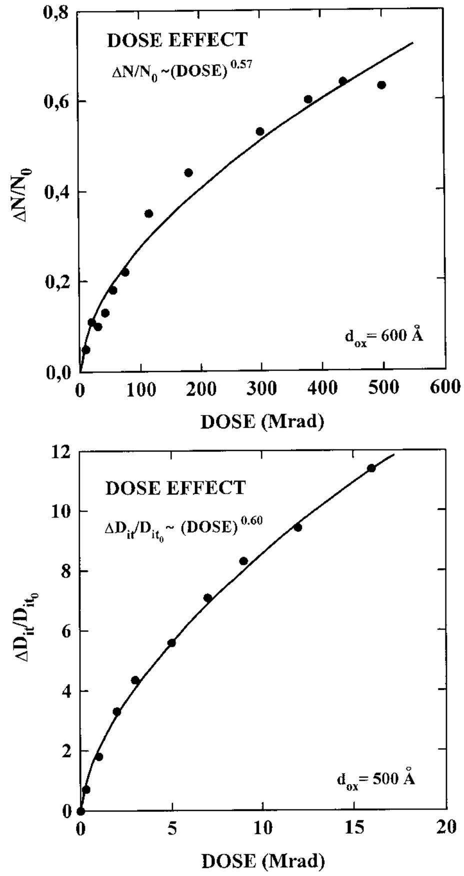

Figure 5. (a) Dopant reduction as a function of x-ray dosage, and (b) normalized interface trap density changes as a function of x-ray dosage. The curves represent a least square fitting to the power law. Device size are 1.22×10^{-2}cm^2, and 1.78×10^{-2}cm^2 respectively.

The possible values for α were observed after irradiating samples with different oxide thickness, stress components, and the type of ionizing radiation. From these we were able to conclude that the values assumed by the exponent α depend strongly of the device processing history prior to irradiation. These data appear to be in very good agreement with published data for the dependence of interface trap density after ionizing radiation exposure of MOS transistors[8], and suggest the dopant reduction to be proportional to the interface trap density generated near the interface. The later could, at very high densities, trap majority carriers yielding the dopant reduction effect.

Another important property associated to the dopant reduction, and never reported before is its time evolution after irradiation. We have found that even after the exposition to the ionizing radiation has ceased the dopant reduction presents a dynamics where the reduction continues to evolute with time as illustrated in figure 6. Curve (a) represents the dopant reduction evolution after irradiation to a dose of 80 Mrad (Si), and curve (b) after a 252 Mrad (Si) irradiation. Two important characteristics arise from this time evolution. First, the time interval after irradiation from which the time dependence starts varies from a few minutes for sample (a), to hundreds of hours for sample (b). Second, the intensity of this time dependence also is reasonably different. This can be explained based on the initial damage level on the vicinity of the SiO_2/Si interface[9] caused by the different dosages irradiated. In both cases the amount of defects generated and/or interface trap density present at the interface may alter the time evolution as observed. These results further support the correlation between the dopant reduction effect with the changes occurring in the interface trap densities of these devices.

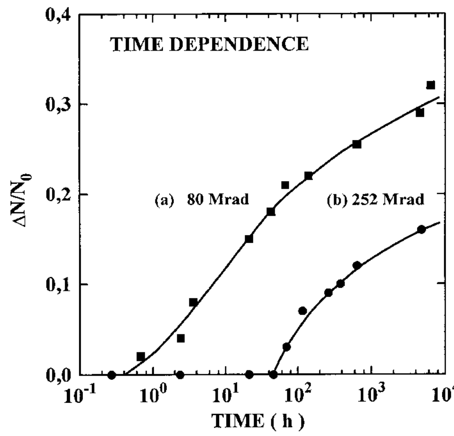

Figure 6. Time Dependence of Dopant Reduction in MOS capacitors after exposure to x-ray irradiation for different dosages. (a) 80 Mrad (Si), and (b) 252 Mrad (Si). Device size are 1.22×10^{-2}cm^2, and 1.78×10^{-2}cm^2 respectively. $d_{ox} = 500$Å.

In addition to these results, we are in the process of changing several device parameters such as the oxide thickness, stress at the interface, processing, device bias during irradiation, and the type of ionizing radiation in order to better understand these effects and unveil the physical mechanisms responsible for these observations.

IV. Summary

In summary, we have studied several effects observed near the SiO_2/Si interface of MOS capacitors when the devices are exposed to doses of ionizing radiation up to 500 Mrad (Si). Reduction of apparent dopant concentration is observed, and its characteristics are analyzed as a function of device size, total dosage, initial damage level, and time evolution. The lack of device size dependence and the time evolution of apparent dopant reduction in MOS devices are reported for the first time.

The dependence of dopant reduction with ionizing radiation dosage indicate a power law dependence in the form $\Delta N/N_0 \sim (dose)^\alpha$, where $1/2 \leq \alpha \leq 1$. The range for possible values of α depends on processing parameters and device history prior to irradiation. In addition, the size, total dosage, initial damage level and time evolution dependence of dopant reduction strongly suggest a correlation between the dopant reduction and the interface trap density generated by the ionizing radiation in the silicon band gap during and after the irradiation.

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